near-point sources to zones with a maximum dimension of about 5 km. Source regions for some of the swarm sequences overlap with those from other sequences, while others occur in spatially distinct regions, suggesting that there are a number of processes causing these events and that some of these processes are repetitive in time. Similarity of waveforms at individual seismic stations during several different swarm sequences further supports the existence of one or more repetitive, long-lived source processes.

S11C-1167 0830h POSTER

Relocating the Hypocenters of an Earthquake Swarm Near Waiouru, South East of Ruapehu, North Island, New Zealand

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Over the past ten years, there has been continuous lower-crustal seismicity in the magnitude range $1.7<=M_L>=4.2$ near Waiouru, 20km south east of Mount Ruapehu, New Zealand, averaging 13 events per month. This study uses the Double-Differencing algorithm of Waldhauser and Ellsworth (2000) to produce precise relative relocations of the hypocenters and thus analyze seismicity, testing whether the swarms origins are tectonic or volcanic. Data comes from a temporary seismic network deployment (CNIPSE) from January to June 2001, which significantly increased the number of stations recording the swarm.

The final relocation reveals earthquakes aligned on a fault-plane oriented 219°, dipping 6°NW, parallel with the surface fault break of the Snow Grass Fault. Composite focal mechanisms reveal normal faulting, oriented 216°, dipping 48°NW. These two fault-plane orientations are parallel, and indicate extension in the Waiouru area. An average b-value of 1.06 over ten years implies tectonic causes.

Activity increased to over 40 events per month in January and March of 1995, coinciding with heating phases in the Ruapehu Crater Lake before the eruption in September 1995. The b-value of the swarm over this period rose to b=1.71, and stayed high through activity in late 1996. Both this high b-value and the temporal correlation suggest the swarm was related to volcanic activity.

Results suggest a complicated relationship between a tectonic swarm associated with propagation of back-arc spreading of the Taupo Volcanic Zone, overprinted with volcanic associations at times of activity on Ruapehu.

S11C-1168 0830h POSTER

Seismic Velocity Structures of Larderello Geothermal System, Italy: Preliminary Results

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The steam-dominated geothermal system of Larderello is located in Tuscany and is the largest Italian area of electricity generation from geothermal resources. Enel Green Power, the main company of the ENEL Group involved in the renewable resources development, has drilled several wells down to maximum depth of about 4.0 km below see level in order to exploit deep and hot steam reservoirs. The explored area is about 400 km^2 with an installed running capacity of about 530 MW. Two steam-dominated reservoirs were found at different depth. The shallowest one at depth of about 1 km, with pressure between 0.2 and 1.5 MPa and temperatures ranging between 150°C and 260°C, is hosted in very permeable carbonate formations (limestone and anhydrite). The deepest reservoir is located in the metamorphic basement up to depth of 3-4 km b.s.l. and is characterized by pressure of about 7.0 MPa and temperature ranging between 300°C and 350°C. Water reinjection is operating in the shallow reservoir of the geothermal area with the aim of both sustaining and increasing reservoir pressures as well as steam production. A network of 26 seismic stations, three of which are three components, permanently records the seismic activity of the Larderello area. Data analysis showed that epicenters span over the whole exploited region even though clusters are visible in particular areas; hypocentral depths are mainly distributed up to 10 km. More detailed hypocenter re-localization might indicate linear features due to regional stress field regime and to the fluid propagation paths into the fracture systems that previously might have been obscured within the seismic clouds. However, precise hypocenter localization calls for high-resolution 3D-velocity model of subsurface structures that is lacking for this area. This study has been addressed to purse this goal and, as a consequence, images of the seismic velocity structures from earthquakes tomographic inversion have been computed. This area was chosen as a suitable test site since the availability of well data can provide a more constrained a priori velocity model. The analyzed data set consists of approximately 500 microearthquakes occurring from January 1994 through September 2000. The estimate duration magnitude ranges between 0-3. The good quality of recorded waveforms allowed us for high precision readings of P- and S- wave first arrivals. Results of a 3D velocity tomographic inversion contributed for a high-quality imaging of subsurface structures in term of Vp and Vp/Vs ratio that may be correlated to the main geological features of the geothermal system.

S11D MCC: 133 Monday 0830h

Forensic Seismology: Exotic Seismic Sources and Man-Made Events I *(joint with OS, PA)*

***Presiding:* K D Koper,** Saint Louis University; **T Wallace,** University of Arizona

S11D-01 0835h INVITED

Forensic Seismology and Nuclear Explosion Monitoring

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Forensic seismology was first termed by H.I.S. Thirlaway in the late 1950s to describe what is now known as verification seismology. In nuclear monitoring it is often the study of anomalous events that for some reason caused an operational system to break down. Examples of events that have elicited study include abnormal mining explosions, mine collapse and rockbursts, earthquakes near nuclear test sites and anomalous nuclear explosions. Analysis of these anomalous disturbances has been the key to understanding source physics. This information in turn, has improved our understanding of the physical basis of seismic event identification, yield estimation, and evasion scenarios. In this talk, we will review examples of anomalous disturbances from different types of sources and how the subsequent analysis led to an improved understanding the effect of source phenomenology on nuclear explosion monitoring.

S11D-02 0855h

Seismology of Impacts

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Impacts of natural and artificial objects can generate significant seismic signals. Such impacts have been recorded by seismometers on a number of occasions. Aside from the public and media interest that such events generate, the signals can exhibit a wide variety of characteristics such that standard discrimination and source identification criteria may fail.

Impact events additionally have the interesting property that the kinetic energy of the impactor is known *a priori* or can be estimated using simple assumptions. This enables estimates of the maximum size and detectability of the seismic signal from any arbitrary impact scenario.

We have assembled a number of such events that have well-recorded on modern seismic systems, and have used the seismic data and information from other sources to develop a relation between the energy of impactor and the corresponding seismic signal. Modelling of the seismic signals has been shown to provide information about the source process. Examples are provided from artificial sources such as aircraft crashes on land and water, from various industrial accidents, and from a variety of natural sources.

S11D-03 0915h INVITED

Seismic Waves Generated by Aircraft Impacts and Building Collapses at World Trade Center, New York City and Shanksville, Pennsylvania on September 11, 2001.

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Seismologists sometimes do their work of data acquisition and analysis against a tragic background. Usually the context is fieldwork far from home, in an area subjected to the natural but sometimes devastating effects of an earthquake. As the appalling events of September 11, 2001 unfolded, we found that we had recorded numerous seismic signals of two plane impacts and building collapses, often at times different than those being reported elsewhere. Collapses of the two World Trade Center (WTC) towers generated the largest seismic waves, observed in five states and up to 428 km away. The North Tower collapse was the largest seismic source and had local magnitude ML 2.3. From this we infer that ground shaking of the WTC towers was not a major contributor to the collapse or damage to surrounding buildings.

The time of plane impact at the Pentagon on September 11, 2001 had often been reported with large scatter. We analyzed seismic records from five stations in the northeastern United States, ranging from 63 to 350 km from the Pentagon to examine whether we could obtain an accurate time of the Pentagon attack based upon our seismic network. Despite detailed analysis of the data, we could not find a clear seismic signal. Even the closest station (Δ= 62.8 km) at Soldier's Delight, Baltimore County, Maryland (SDMD) did not record the impact. However, we positively identified seismic signals associated with United Airlines Flight 93 that crashed near Shanksville, Somerset County, Pennsylvania. The time of the plane crash was 10:06:05±5 (EDT). We recognized that information on accurate timing of earthquakes and other events is very desirable for emergency management agencies and government authorities handling mitigation efforts as well as for general public, and that the modern seismographic stations with accurate clocks can provide such reference time as long as there are discernable ground motion associate with such sources.

S11D-04 0935h

A Case Study in Forensic Seismology: The 1998 Natural Gas Pipeline Explosion Near Carlsbad, New Mexico

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On August 19, 2000 two seismometer networks in southeastern New Mexico recorded signals from a natural gas pipeline explosion. The explosion killed 12 members of an extended family that had been camping on the banks of a nearby river. Analysis of the particle motion, arrival times, and durations of the seismic signals indicate that three impulsive events occurred with origin times of 11:26:18.8 ± 1.9, 11:26:43.6 ± 2.1, and 11:27:01.7 ± 2.0 (GMT). Each event generated an R_g wave with group velocity of 1.7-2.0 km/s and an air-coupled Rayleigh wave with a group velocity of about 345 m/s. The air-coupled Rayleigh waves had especially large amplitudes because of a geometric waveguide created by an atmospheric temperature inversion at the time of the accident. The first event was due to the explosive blowout of the buried, high-pressure pipeline while the second event was due to the ignition of the vented natural gas. The nature of the third event is unclear, however it was likely created by a secondary ignition. There were also two extended seismic events

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that were coeval with the first two impulsive events. The first resulted from the pre-ignition venting of the gas and lasted for about 24 s, while the second resulted from the post-ignition roaring of the flames and lasted for about one hour. Many of the source constraints provided by the seismic data were not available from any other investigative technique and so were valuable to a diverse range of parties including the New Mexico State Police, law firms involved in litigation related to the accident, the National Transportation and Safety Board, and the general public. Especially important was the seismically derived time between the blowout and ignition. The 24.0 s lag indicates that the initial rending of the pipe did not cause the ignition and that a more likely source was the nearby campsite, and it also significantly affected the amount of punitive damages the families of the victims were due since the victims were in a state of extreme distress during that period of time.

S11D-05 0950h

Forensic Analysis of Seismic Events in the Water; Submarines, Explosions and Impacts

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Sudden pressure changes in a water column can generate significant seismic energy that may be recorded on land based seismometers. In recent years a number of accidents and chemical explosions in the ocean or large lakes have been recorded at teleseismic distances, affording the opportunity to investigate the seismic source. The August 2000 sinking of the Russian attack submarine Kursk is the most famous example of an accident at sea that seismology played a role in understanding, but many other exist including: (1) the 1989 sinking and apparent implosion of the Soviet submarine Komsomoltes, (2) the sudden sinking of a large oil drilling platform in the North Sea in 1991, (3) the 1972 explosion and sinking of a 700 ton cargo ship off the coast of southwestern England, and (4) the crash of Swissair Flight 111 off the coast of Nova Scotia in 1998.

Enough empirical information has been collected to accurately characterize the size of most of these underwater (or on the surface of the water) events. Further, many of the seismic signals contain a spectral scalloping that can be interpreted as either as reverberation of seismic energy in the water column or bubble pulses from underwater explosions. This information can be used to constrain the details of the seismic source. For example, the Kursk explosion had a pronounced spectral scalloping with a 1.45 Hz banding. Using a relationship between bubble pulse frequency, explosive yield and depth of detonation (the relationship was developed and verified using a large population of chemical explosions in the 1940s), the Kursk detonation is estimated to be at a depth of 85-100 m, with a yield of 3-5 tonnes equivalent TNT. This seismic result was confirmed almost exactly by the Russian government with the release of the official accident on the Kursk in August 2002.

Seismic events in the water column can be rich sources of information about the details of the source. Events as small as magnitude 1.2 are routinely recorded by stations around the world, and in the future as seismic networks are upgraded, more events will be recorded. This data can, and should be, fully exploited to understand exotic events.

S11D-06 1025h INVITED

Hydroacoustic Signals Recorded by the International Monitoring System

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Networks of hydrophones, such as the hydroacoustic part of the International Monitoring System (IMS), and hydrophone arrays, such as the U.S. Navy operates, record many types of signals, some of which travel thousands of kilometers in the oceanic sound channel. Abyssal earthquakes generate many such individual events and occasionally occur in swarms. Here we focus on signals generated by other types of sources, illustrating their character with recent data, mostly from the Indian Ocean. Shipping generates signals in the 5-40 Hz band. Large airgun arrays can generate T-waves that travel across an ocean basin if the near-source seafloor has appropriate depth/slope. Airgun array shots from our 2001 experiment were located with an accuracy of 25-40 km at 700-1000 km ranges, using data from a Diego Garcia tripartite sensor station. Shots at greater range (up to 4800 km) were recorded at multiple stations but their higher background noise levels in the 5-30 Hz band resulted in location errors of 100 km. Imploding glass spheres shattered within the sound channel produce a very impulsive arrival, even after propagating 4400 km. Recordings of the sphere signal have energy concentrated in the band above 40 Hz. Natural sources such as undersea volcanic eruptions and marine mammals also produce signals that are clearly evident in hydrophone recordings. For whales, the frequency range is 20 120Hz and specific patterns of vocalization characterize different species. Volcanic eruptions typically produce intense swarms of acoustic activity that last days-weeks and the source area can migrate tens of kms during the period. The utility of these types of hydroacoustic sources for research and/or monitoring purposes depends on the accuracy with which recordings can be used to locate and quantitatively characterize the source. Oceanic weather, both local and regional, affect background noise levels in key frequency bands at the recording stations. Databases used in forward modeling of propagation and acoustic losses can be sparse in remote regions. Our Indian Ocean results suggest that when bathymetric coverage is poor, predictions for 8 Hz propagation/loss match observations better than those for propagation of 30 Hz signals over 1000-km distances.

S11D-07 1045h

Detecting Ocean Climate Change in Seismic Noise: the Need for Directional Information

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Ocean-generated microseisms are signals recorded continuously at virtually every seismic station. Although a hindrance for earthquake studies, microseismic noise contains a wealth of information in its generation and propagation characteristics.

Recent hindcasting efforts for ocean climate change use seismic records on land as a proxy for past ocean wave heights. These studies rely on a strong amplitude correlation between ocean waves and microseisms. Using recent ocean wave models and southern California seismic data, we demonstrate the importance of the propagation direction of storm swells and microseisms for climate hindcasting.

Time-lapse movies of ocean swells and concurrent microseism polarizations and array beam azimuths reveal a direct causal relationship between swells arriving at different North American coastal areas and the triggered microseism directions. We find dominant source areas for microseismic noise observed in southern California as distant as Newfoundland and British Columbia, and show that microseism amplitudes strongly depend on swell direction, which suggests the use of directional rather than only amplitude information for climate hindcast studies.

S11D-08 1100h

Ocean Infragravity Waves and Shaking Earth: Cause of Broad Peak at 0.01 Hz in the Seismic Noise Spectrum

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It is well known that low-frequency seismic noise below 0.003 Hz is caused by atmospheric effects. At higher frequencies, at about 0.05-0.15 Hz, seismic noise has another peak(s) (microseism), which is known to be caused by ocean waves near the coast. It has been pointed out by multiple authors recently that, between these two well known peaks, there is a broad peak at about 0.01 Hz.

The purpose of this paper is to point out that this broad peak is caused by gravity waves in the ocean. We show this by computing theoretical power spectral density for surface acceleration and comparing it with observed seismic data: it is now well known that infragravity waves are ubiquitous and make distinct spectral characteristics in the sea-bottom pressure data (Webb, 1986; Webb et al., 1991). Assuming that these pressure variations at sea bottom drive excitaion of solid earth modes, we derived a normal mode formula for power spectral density of acceleration. Using a typical pressure value reported in the literature (Webb, 1998), we evaluated it quantitatively. The results clearly a show existence of broad peak in the noise spectra at about 0.01 Hz and match overall trend of observed spectra very well.

In this paper, we will mainly report results on global average. But this mechanism predicts spatial and seasonal variations of noise amplitudes because ocean waves (significant wave heights) typically show latitude and seasonal variations which must also be related to sea bottom pressure changes. Analysis of these aspects of data will lead to noise amplitude variations among seismic stations and its systematic understandings.

S11D-09 1115h

HYDROACOUSTIC SIGNALS FROM HUGE ICEBERGS IN THE ROSS SEA

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Hydroacoustic signals detected in Late 2000 by seismic stations of the Polynesian network are shown to originate from huge icebergs which at the time were drifting in the Ross Sea after calving off the Ross Ice shelf. The signals present a broad variety of spectral characteristics, most of them featuring prominent eigenfrequencies in the 4-to-7 Hz range, often complemented by overtones. They can last as little as a few mn or as long as 3 hours. Most epicenters, obtained by combining observations of distant hydroacoustic and regional seismic records, follow the spatiotemporal evolution of the drift of iceberg B15-B. Most of the signals are generated during a 36-day time window when it is speculated that B15-B collided with smaller icebergs or was scraping the ocean floor on the shallow continental shelf. We speculate on the possible physical nature of the resonator generating the signals, which could correspond to an elastic mode of the iceberg, or to the oscillation of the fluid-filled crack in the ice.

S11D-10 1130h

The 2001-2002 Volcanoseismic Swarm near Pitcairn Island

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A vigorous seismic swarm took place between 29 Oct. 2001 and December 2001 in the vicinity of Pitcairn Island, Southcentral Pacific. Four events were reported by the IDC, with a maximum magnitude of 4.0 on Nov. 15 and Nov. 21. An additional 230 events were detected by the RSP station at Rikitea, 575 km to the West of Pitcairn. Examination of the entire time series of the IRIS station at Pitcairn Island (PTCN) from Oct. 1, 2001 to Dec. 31, 2001 resulted in the identification of a major swarm of seismic activity comprising at least 3250 events above magnitude 1, with maxima of activity from Nov. 9 to Nov 26, and Dec. 10 to Dec. 25. It is estimated that as many as 20,000 events could be identified at lower magnitudes. The epicenter of the swarm is constrained from timing of crustal Sg and Pg phases at PTCN, and polarization of S phases, to lie approximately 25-50 km from the

island in either a NW or a SE azimuth. A preliminary frequency-magnitude investigation shows a high b-value (2.14), suggestive of volcanic activty, an interpretation supported by the recording of episodes of tremors in the frequency band 2-8 Hz. This swarm is reminiscent of activity at Mehetia-Teahitia (Society Islands) in 1981-1985. Additional signals were picked at Rikitea in March, April and as late as 24 July 2002.

S11D-11 1145h

Observations of Deep Long-Period (DLP) Seismic Events Beneath Aleutian Arc Volcanoes; 1989 to 2002

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Between October 1989 and September 2002 the Alaska Volcano Observatory (AVO) located 149 Deep Long-Period events (DLP) at nine volcanic centers in the Aleutian arc. Many more were detected but could not be located reliably. These events occur at mid- to lower- crustal depths (10 to 50 km) and are characterized by emergent phases, extended codas, and a strong spectral peak generally between 2 and 4 Hz. Observed wave velocities and particle motions indicate that the dominant phases are P- and S-waves. The average reduced displacement of Aleutian DLPs is 28 cm2 and the largest event has a reduced displacement of 589 cm2 (or ML 2.5). DLP epicenters often extend over broad areas (5 to 30 km) that surround active volcanoes. DLP events are often highly clustered in time, with several occurring over a period of 3 to 30 minutes. Within these clusters individual DLPs are often separated by lower amplitude volcanic tremor with a similar spectral character. Higher frequency signals and/or volcano-tectonic earthquakes at similar depths are occasionally associated with DLP clusters.

DLPs have now been identified at a number of volcanoes including Mammoth Mountain in 1989 and Mount Pinatubo in 1991, where they have been linked to the movement of basaltic magma. At most Aleutian volcanoes DLPs appear to occur as part of background seismicity. A likely explanation is that they reflect a relatively steady-state process of ascent of mafic magma over broad areas in lower and middle portions of the crust. At Mount Spurr DLP seismicity was initiated by the 1992 eruptions and then slowly declined until 1997, suggesting these events reflect changes in magma flux caused by the depressurization of the magmatic system during the eruptions. At Shishaldin Volcano small, short-lived increases in DLP seismicity occurred about nine months prior to the 19 April 1999 eruption and again roughly five weeks after the eruption, suggesting a link between eruptive activity and magma flux in the mid- to lower-crust. The occurrence of DLPS prior to eruptions at Pinatubo and Shishladin suggests that these events may provide some of the earliest indication of renewed volcanic unrest.

S12A MCC: Hall C Monday 1330h

Forensic Seismology: Exotic Seismic Sources and Man-Made Events II Posters *(joint with OS, PA)*

Presiding: **R C Aster,** New Mexico Institute of Mining and Technology**; R Bulow,** Scripps Institution of Oceanography

S12A-1169 1330h POSTER

Far-Field Energy Radiation From a Building Under Harmonic Excitation

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A nine story building on the Caltech campus (Millikan Library) was harmonically excited at its East-West (EW) and North-South (NS) natural frequencies to determine the behavior of the far-field radiated waves emanating from the building. The building's natural frequencies are $\sim$ 1.12 Hz. and $\sim$ 1.64 Hz. for the EW and NS directions respectively, and the individual building shakes lasted approximately four hours each. We use the data recorded by the Southern California TriNet stations, and the building's signal can be observed at distances larger than 300 kilometers. By using 36 USGS owned FBA-11 accelerometers located in the building to compute the forces in each floor, we can estimate the maximum applied forces/overturning moments that the building imparts on the soil to be: Shear Force $\sim$ 2.2e+5 N (4.9e+4 lbf) and Overturning Moment $\sim$ 7.0e+6 Nm (5.2e+6 lbf ft) for the EW shake, and Shear Force $\sim$ 5.2e+5 N (1.2e+5 lbf) and Overturning Moment $\sim$ 1.6e+7 Nm (1.2e+7 lbf ft) for the NS shake. Furthermore, by using the roof displacement and the force being applied to the building, we estimate the horsepower being used by the motor that powers the shaker as $\sim$ 12 J/sec (0.02 hp) for the EW shake, and $\sim$ 40 J/sec (0.05 hp) for the NS shake. The units used above are as follows: N = Newton, lbf = Pound Force, m = Meter, ft = Feet, J = Joule, sec = Second, and hp = Horsepower.

From the measured signals, we produce maximum amplitude plots (as the measured waves are harmonic) for each component as well as the vector sum of the components, and we find the best fitting distance decay rates for the data. We observe very little radiation pattern in the radiated waves, which is contrary to the simple half-space models and we explore the lack of azimuthal radiation patterns from the building. It is interesting to note that the best fitting distance decay rate changes at a distance of approximately 50 kilometers.

This approach is nondestructive and repeatable and thus is suitable for establishing (monochromatic) amplitude response curves of the crust and mantle structure in Southern California. Furthermore, this may also be a powerful tool to monitor temporary variations of site response changes if they ever occur.

S12A-1170 1330h POSTER

Coal-Mining Seismicity in the Trail Mountain Area, Utah: Part I–Case Study for Assessing Ground-Shaking Hazard

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We report results from a multipart study aimed at quantifying the potential ground-shaking hazard to Joes Valley Dam (a 58-m-high earthfill dam) posed by mining-induced seismicity (MIS) from future underground coal mining as close as $\sim$1 km. In order to characterize future MIS close to the dam, we studied MIS located $\sim$3-6 km from the dam at the then active Trail Mountain (TM) Mine. A 12-station local seismic array (11 stations above ground, one below, combining 8 triaxial accelerometers and varied velocity sensors) was strategically operated in the TM area from October 2000 through April 2001 for the dual purpose of (1) continuously monitoring and accurately locating (<1 km) MIS associated with longwall mining at a depth of 0.5-0.6 km and (2) capturing high-quality ground-motion recordings at distances of $\sim$0.2 to 9 km for the larger events. (Ground-motion attenuation relationships and moment-tensor results are reported in a companion abstract.)

Using a data set of 1,913 earthquakes ($M \leq 2.2$), we analyzed space-time variations of MIS, temporal variations in rate and magnitude, and source-mechanisms. Observed MIS was highly correlated with mining activity in both space and time. Most of the better-located events had depths conservatively constrained within $\pm$0.6 km of mine level. Only 2 percent of the 1,913 located events were recorded with at least one compressional P-wave first motion–implying either (a) non-observation of compressional P-wave first motions was due to consistent undersampling, (b) dominance of an implosional or collapse-type source mechanism (rather than shear-slip type), or (c) some combination of the above. We assessed a probable maximum magnitude of M_W 3.9(84th percentile of cumulative distribution) for potential MIS close to Joes Valley Dam based on both the global and regional record of coal-mining-related MIS as well as local geology and mining scenarios.

S12A-1171 1330h POSTER

Coal-Mining Seismicity in the Trail Mountain Area, Utah: Part II-Ground Motion Prediction Equations and Seismic Moment Tensors

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As part of a study to assess the seismic hazard to the Joes Valley Dam from future coal mining in its environs, we analyzed recordings from a local broad-band array, operated by the University of Utah centered on the Trail Mountain coal mine, which is also near the Joes Valley Dam and from the Willow Creek mine about 50 km to the north. Seismic moment tensors determined for a small suite of events at Trail Mountain typically have a large implosive volume component of similar magnitude to the shear (normal) component suggesting that these earthquakes are tightly-coupled to collapse of the mine at depths near 500 m. The moment tensors also showed that the moment magnitude had no consistent bias with respect to the coda magnitudes Mc, assigned by the University of Utah. With this improved understanding of the seismic sources in this mining region, we used accelerograms from 12 earthquakes, with especially high signal/noise and magnitudes ranging from 1 to 4.2, to develop ground motion prediction equations suitable for assessing the hazard to the Joes Valley Dam following the method of Joyner and Boore (1988). The parameters peak acceleration, peak velocity, and pseudovelocities, at 5 % damping and periods ranging from 0.1 to 2 s, were modeled by ground motion prediction equations that account for linear magnitude dependence, geometrical spreading, anelasticity and scattering, and site effects. The resulting prediction equations agree well with those developed for earthquakes, with much higher magnitudes in active tectonic settings, but the new prediction relation typically has a stronger fall-off with distance. In any case, these prediction results for the Trail Mountain region, combined with an estimate of the maximum probable earthquake, from a companion study, yield a well-constrained seismic hazard assessment for the Joes Valley Dam due to future coal mining nearby. These new ground motion prediction equations would be appropriate for assessing seismic hazard from shallow seismicity in active tectonic regions.

Joyner W.B., and D.M. Boore (1988) Measurement, characterization, and prediction of strong ground motion, *Proceedings of Earthquake Engineering and Soil Dynamics, II, GT Div/ASCE Park City, Utah, June 27-30.*

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Analysis of Seismicity Recorded at an Underground Coal Mine During a Fatal Fire and Explosion Sequence

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On July 31, 2000 a sequence of four explosions occurred at the Willow Creek underground coal mine (Helper, UT) killing two miners and injuring 8 others. An investigation by the Mine Safety and Health Administration (MSHA) points to a roof fall as the most likely source of ignition of methane and other gaseous hydrocarbons which led to the explosions. NIOSH operated a seismic monitoring system at the mine in 1998-2000. Seismicity recorded by the underground array prior to and during the explosion sequence has been analyzed in an attempt to place constraints on the initial ignition source. Velocity sensors (4.5 Hz) were deployed in a 12-station underground array measuring 0.9 by 2.2 km. Throughout mining of the D-3 longwall panel, rates of seismic event occurrence, face advance, and methane accumulation were observed to be closely correlated indicating a strong association between longwall caving/deformation processes and gas release. At the approximate time of the first explosion a low-amplitude, emergent multiple-pulse seismic signal was observed which is interpreted to be the seismic signature of the first explosion. Features characteristic of caving- or fracture-related events are absent indicating that it was not accompanied nor preceded by such an event at least within the few seconds of recorded pre-trigger time. The preceding seismic event that was large enough to be recorded by the seismic monitoring system occurred 11 minutes before the first explosion. This observation does not rule out the possibility of a smaller fall that may have been ejected into the mine opening with damaging force but was not large enough

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